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# Large-$N_c$ Quark Distributions in the Delta and Chiral Logarithms in Quark Distributions of the Nucleon

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## Abstract

In a world with two quark flavors and a large number of colors ($N_c$), the polarized and unpolarized quark distributions in the delta are completely determined by those in the nucleon up to relative $\mathcal{O}(1/N_c^2)$. In particular, we find $q_\Delta(x) = \left[(1 \pm 2T_z)u_N(x) + (1 \mp 2T_z)d_N(x)\right]/2\left(1 + \mathcal{O}(1/N_c^2)\right)$ and $\Delta q_\Delta(x) = \left[(5 \pm 2T_z)\Delta u_N(x) + (5 \mp 2T_z)\Delta d_N(x)\right]/10\left(1 + \mathcal{O}(1/N_c^2)\right)$, where $q = u, d$ and $T_z$ the charge state of a delta. The result can be used to estimate the leading chiral-logarithmic corrections to the quark distributions in the nucleon.

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Among baryon resonances, the delta is very special: In a world with two quark flavors and a large number of colors ($N_c$), consistency conditions for meson-baryon scattering imply that there is a (nearly) degenerate hadron multiplet with quantum numbers $J = T = 1/2,\ 3/2,\ ...,\ N_c/2$ [1, 2]. In the real world of $N_c = 3$, the delta resonance and the nucleon can be identified with this multiplet. Hence many properties of the delta in the limit of $N_c \to \infty$ can be related to those of the nucleon by simple Clebsch-Gordon coefficients. Many of these relations, particularly those accurate to order $1/N_c^2$, are shown to be valid in data at 10% level [1, 3, 4].

In this paper, we explore the large-$N_c$ constraint on the quark distributions in the delta. We show that the unpolarized up and down quark distributions in the delta ($\Delta$) are related to those in the nucleon ($N$) by

$$q_\Delta(x) = \frac{1}{2}\left[(1 \pm 2T_z)u_N(x) + (1 \mp 2T_z)d_N(x)\right]\left(1 + \mathcal{O}(1/N_c^2)\right) \ , \tag{1}$$

where $q = u, d$, and $T_z$ specifies the charge state of a delta. In particular, the distributions in the $\Delta^+$ and the nucleon ($N$) are the same. Since these distributions are of order $N_c$, their ratios in $\Delta^+$ and $N$ are equal to 1 up to corrections of order $1/N_c^2$. Similar relations are found for the quark helicity and transversity distributions [5]:

$$\begin{aligned}
\Delta q_\Delta(x) &= \frac{1}{10}\left[(5 \pm 2T_z)\Delta u_N(x) + (5 \mp 2T_z)\Delta d_N(x)\right]\left(1 + \mathcal{O}(1/N_c^2)\right) \ , \\
\delta q_\Delta(x) &= \frac{1}{10}\left[(5 \pm 2T_z)\delta u_N(x) + (5 \mp 2T_z)\delta d_N(x)\right]\left(1 + \mathcal{O}(1/N_c^2)\right) \ .
\end{aligned} \tag{2}$$

Using the above relations, we can make estimates of the delta contributions to the leading chiral-logarithms in the quark distributions of the nucleon [6, 7, 8]. The interplay between chiral behavior and large $N_c$ quantities is reminiscent of what is seen for static baryon properties [9]. The quark distributions in the delta, particularly the nucleon-delta transition distribution:

$$\Delta u_{N\Delta}(x) - \Delta d_{N\Delta}(x) = \sqrt{2}(\Delta u_N(x) - \Delta d_N(x))\left(1 + \mathcal{O}(1/N_c^2)\right) \tag{3}$$

can be used to understand the parton distributions in nuclei [12]. Some large $N_c$ results about the $N - \Delta$ transition off-forward distributions were discussed in Ref. [11]. Finally, the $\Delta$ distributions can be calculated on a lattice when the quark masses are sufficiently large and a stable delta exists.

In the large-$N_c$ limit, all baryons including the nucleon and the delta are infinitely heavy. For simplicity we assume they have a four-velocity $v^\mu$ and, without loss of generality, we take $v^\mu = (1, 0, 0, 0)$. The spin-flavor wave function of a baryon state $|J = T, J_z, T_z\rangle$ can be taken as a product of the complete symmetric tensors $\psi^{(\alpha_1\alpha_2...\alpha_{2J})} \sim \psi_{JJ_z}$ and $\chi^{(a_1a_2...a_{2J})} \sim \chi_{JT_z}$ in the spin and flavor spaces, respectively. Introduce the following twist-two quark operators,

$$\begin{aligned}
O_q^{\mu_1\cdots\mu_n} &= \overline{q}\gamma^{(\mu_1}iD^{\mu_2}\cdots iD^{\mu_n)}q \ , \\
O_{\Delta q}^{\mu_1\cdots\mu_n} &= \overline{q}\gamma^{(\mu_1}\gamma_5 iD^{\mu_2}\cdots iD^{\mu_n)}q \ , \\
O_{\delta q}^{\alpha\mu_1\cdots\mu_n} &= \overline{q}\sigma^{[\alpha(\mu_1]}\gamma_5 iD^{\mu_2}\cdots iD^{\mu_n)}q \ ,
\end{aligned} \tag{4}$$

where $(\cdots)$ and $[\cdots]$ denote, respectively, the symmetrization and antisymmetrization of the

by dividing $n+2$ powers of a baryon mass. [Since the nucleon and delta masses differ at order $1/N_c$, one can take either mass without affecting the result.] Considering those components which survive the non-relativistic limit, we define

$$\begin{aligned}\mathcal{O}_q^{(n)} &= O_q^{(00\cdots0)} N_c^3/M^{n+2} \ , \\ \mathcal{O}_{\Delta q}^{(n)i} &= O_{\Delta q}^{(i0\cdots0)} N_c^3/M^{n+2} \ , \\ \mathcal{O}_{\delta q}^{(n)i} &= O_{\delta q}^{(i0\cdots0)} N_c^3/M^{n+2} \ . \end{aligned} \quad (5)$$

The matrix elements of the above operators in the baryon multiplet are

$$\begin{aligned}\left\langle J, J_z, T_z \left| \mathcal{O}_q^{(n)} \right| J, J_z, T_z \right\rangle &= \left\langle x^{n-1} \right\rangle_q v^{(0} \cdots v^{0)} \ , \\ \left\langle J, J_z, T_z \left| \mathcal{O}_{\Delta q}^{(n)i} \right| J, J_z, T_z \right\rangle &= \left\langle x^{n-1} \right\rangle_{\Delta q} \psi_{JJ_z}^\dagger J^{(i} v^0 \cdots v^{0)} \psi_{JJ_z} \ , \\ \left\langle J, J_z, T_z \left| \mathcal{O}_{\delta q}^{(n)i} \right| J, J_z, T_z \right\rangle &= \left\langle x^{n-1} \right\rangle_{\delta q} \psi_{JJ_z}^\dagger J^{[i} v^{(0]} v^0 \cdots v^{0)} \psi_{JJ_z} \ . \end{aligned} \quad (6)$$

The coefficients in front of the various structures are the moments of the unpolarized and polarized quark distributions:

$$\begin{aligned}\left\langle x^{n-1} \right\rangle_q &= \int_0^1 dx x^{n-1} \left( q(x) + (-1)^n \overline{q}(x) \right) \ , \\ \left\langle x^{n-1} \right\rangle_{\Delta q} &= \int_0^1 dx x^{n-1} \left( \Delta q(x) + (-1)^{n-1} \Delta \overline{q}(x) \right) \ , \\ \left\langle x^{n-1} \right\rangle_{\delta q} &= \int_0^1 dx x^{n-1} \left( \delta q(x) + (-1)^n \delta \overline{q}(x) \right) \ , \\ & (n = 1, 2, 3, ...) \end{aligned} \quad (7)$$

The isospin dependence of the above distributions is implicit. When we refer to the quark distributions in the nucleon, we mean those in the proton ($T_z = 1/2$). For the delta, unless stated otherwise, we mean the +1 charge state, i.e., $\Delta^+$ with $T_z = 1/2$.

We now consider quark distributions in the delta separately for different spin-isospin channels:

1. **Scalar-isoscalar channel**:

Consider the unpolarized isoscalar quark distribution $u(x)+d(x)$. Its moments are defined as the matrix elements of the twist-two operators $\mathcal{O}_{u+d}^{(n)}$. Expressed in terms of quark and gluon fields, the operators are sums of one- and many-body quark-gluon operators. When inserted in between baryon states, all contributions are of order $N_c \cdot N_c^{1-n}$ ( where the second factor comes from the trivial normalization factor in Eq. (5)). Therefore, in the limit of $N_c \to \infty$, $u(x) + d(x)$ scales as $N_c^2 \phi(xN_c)$, where $\phi(x)$ is an $N_c$ independent function [10].

All operators $\mathcal{O}_{u+d}^{(n)}$ are spin and isospin-independent. Therefore, like the baryon masses, they can be expanded in terms of the angular momentum operator $J$ [3]

$$\mathcal{O}_{u+d}^{(n)}/N_c^{2-n} = a_0^{(n)} + a_1^{(n)} \left( \frac{J}{N_c} \right)^2 + ... \ , \quad (8)$$

where $a_0^{(n)}$ and $a_1^{(n)}$ are constants of order 1 in $N_c$ counting. Here we have neglected possible

nucleon ($J = 1/2$) and the delta ($J = 3/2$) are the same up to corrections of relative order $(1/N_c)^2$. We therefore conclude that the $u(x) + d(x)$ distributions in the nucleon and delta are related through

$$\frac{u_N(x) + d_N(x)}{u_\Delta(x) + d_\Delta(x)} = 1 + \mathcal{O}(1/N_c^2) \ . \tag{9}$$

The above relations are true for any charged state of the nucleon and delta.

The result has an immediate application. The leading chiral logarithms of the quark distributions in the nucleon can be calculated in heavy-baryon chiral perturbation theory [7, 8]. The generalization to large-$N_c$ chiral perturbation theory is straightforward. In this expansion, $m_\pi \to 0$, $N_c \to \infty$, and $m_\pi N_c$ fixed. The delta contribution to the leading chiral behavior of the moments of the $u(x) + d(x)$ distribution in the nucleon was calculated in Ref. [8]. The result is

$$\delta\langle x^{n-1}_{(u+d)N}\rangle_{\text{from }\Delta} = -4\frac{g^2_{\pi N\Delta}}{(4\pi f_\pi)^2} J_1(\Delta, m_\pi) \left(\langle x^{n-1}_{(u+d)N}\rangle^0 - \langle x^{n-1}_{(u+d)\Delta}\rangle^0\right) \ , \tag{10}$$

where

$$J_1(\Delta, m_\pi) = (m_\pi^2 - 2\Delta^2)\log\left(\frac{m_\pi^2}{\mu^2}\right) + 2\Delta\sqrt{\Delta^2 - m_\pi^2}\log\left(\frac{\Delta - \sqrt{\Delta^2 - m_\pi^2 + i\epsilon}}{\Delta + \sqrt{\Delta^2 - m_\pi^2 + i\epsilon}}\right) \ , \tag{11}$$

and $g_{\pi N\Delta}$ is the $\pi$-$N$-$\Delta$ coupling, and $\Delta$ is the delta-nucleon mass difference. The superscript 0 labels the moments in the chiral limit. Since $g_{\pi N\Delta} \sim N_c$, $f_\pi \sim \sqrt{N_c}$, $\langle x^{n-1}_{(u+d)N}\rangle^0 - \langle x^{n-1}_{(u+d)\Delta}\rangle^0 \sim 1/N_c^{-n}$, the above correction is of order $N_c^{1-n}$ in $N_c$ counting. Hence the chiral corrections are subleading both in $m_\pi/4\pi f_\pi$ and in $1/N_c$.

2. **Scalar-isovector channel**:

The unpolarized isovector distribution $u(x) - d(x)$ is defined in terms of the twist-two operators $\mathcal{O}^{(n)}_{u-d}$. Because of the cancellation from the up and down quark contributions, the matrix elements in the nucleon and delta states are of order $N_c^{1-n}$ in $N_c$ counting. These operators can be expanded as [3],

$$\mathcal{O}^{(n)}_{u-d}/N_c^{1-n} = a_0^{(n)} T^3 + a_1^{(n)}\frac{J^i G^{i3}}{N_c} + a_2^{(n)}\frac{J^2 T^3}{N_c^2} + \ldots \ , \tag{12}$$

where $G^{ia}$ are generators of spin-flavor SU(4). For two flavors, $4J_i G^{ia} = (N_c + 2)T^a$. [4] From the above expansion, we conclude that the $u - d$ distributions in the proton and the $\Delta^+$ are the same up to order $1/N_c^2$,

$$\frac{u_N(x) - d_N(x)}{u_{\Delta^+}(x) - d_{\Delta^+}(x)} = 1 + \mathcal{O}(1/N_c^2) \ . \tag{13}$$

Combining the relations in Eqs. (9) and (13), we have

$$u_\Delta(x) \ = \ \left\{\left(\frac{1}{2} + T_z\right) u_N(x) + \left(\frac{1}{2} - T_z\right) d_N(x)\right\}\left(1 + \mathcal{O}(1/N_c^2)\right) \ ,$$

Here we have allowed the delta in a general charge state, $T_z$.

Consider now the chiral logarithms in the $u(x) - d(x)$ distribution in the nucleon. The delta contribution is ($n > 1$), [8]

$$\delta\langle x^{n-1}_{(u-d)N}\rangle_{\text{from }\Delta} = -\frac{4g^2_{\pi N\Delta}}{(4\pi f_\pi)^2} J_1(\Delta, m_\pi)\left(\langle x^{n-1}_{(u-d)N}\rangle^0 - \frac{5}{3}\langle x^{n-1}_{(u-d)\Delta^+}\rangle^0\right) \ . \qquad (15)$$

To make an estimate, we assume the large-$N_c$ relations,

$$\begin{aligned} g_{\pi N\Delta} &= \frac{3}{2\sqrt{2}} g_A \ , \\ \langle x^{n-1}_{(u-d)N}\rangle^0 &= \langle x^{n-1}_{(u-d)\Delta^+}\rangle^0 \ . \end{aligned} \qquad (16)$$

Then the contribution from Eq. (15) plus that from the $\pi$-$N$ loop [7, 8] yields,

$$\delta\langle x^{n-1}_{(u-d)N}\rangle = C_n \frac{1}{(4\pi f_\pi)^2}\left[3g_A^2 J_1(\Delta, m_\pi) - (3g_A^2 + 1) m_\pi^2 \log\left(\frac{m_\pi^2}{\mu^2}\right)\right] \ , \qquad (17)$$

where $C_n = \langle x^{n-1}_{(u-d)N}\rangle^0$. Each term in the square bracket is of order $N_c^2$; however, the nucleon and delta contributions cancel up to and including order $N_c$, where the large $N_c$ limit is taken with fixed $m_\pi$. The remaining contribution is of order $N_c^0$; and hence the chiral correction is again subleading in $1/N_c$. In the real world, the delta contribution has the same sign as the nucleon contribution and is about twice in magnitude. Of course, the analytical contributions there might not be so small compared with the non-analytical ones considered here.

3. **Vector-isovector channel**:

Now we turn to the quark helicity distributions in the delta. First, let us consider the isovector distribution $\Delta u(x) - \Delta d(x)$. The corresponding twist-two operators $\mathcal{O}^{(n)i}_{\Delta u - \Delta d}$ is proportional to the vector-isovector operator $J^i T^a$. Thus, in the large-$N_c$ limit, their matrix elements are proportional to $N_c \cdot N_c^{1-n}$. Using the same arguments for the pion-baryon coupling or isovector magnetic moment [1, 4], we find that the ratio of the distribution in the delta and nucleon is that of the spin-isospin Clebsch-Gordon coefficients,

$$\frac{\Delta u_\Delta(x) - \Delta d_\Delta(x)}{\Delta u_N(x) - \Delta d_N(x)} = \frac{2T_z}{5} + \mathcal{O}(1/N_c^2) \ . \qquad (18)$$

where again $T_z$ is the isospin projection of the delta. In particular, for the $\Delta^+$ state, the ratio is $1/5$. Similarly, we have the relation for the transversity distribution

$$\frac{\delta u_\Delta(x) - \delta d_\Delta(x)}{\delta u_N(x) - \delta d_N(x)} = \frac{2T_z}{5} + \mathcal{O}(1/N_c^2) \ . \qquad (19)$$

To find the delta contribution to the leading chiral logarithms in $\Delta u_N(x) - \Delta d_N(x)$, we need to define the spin-dependent delta-nucleon transition distribution, $\Delta q_{N\Delta}(x)$ [12]. Its moments are defined by the matrix elements,

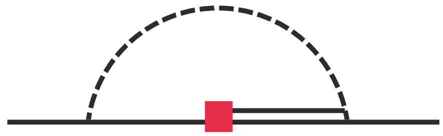

FIG. 1: Contribution to the chiral logarithms in the quark distribution $\Delta u(x) - \Delta d(x)$ of the nucleon from the $N - \Delta$ transition distribution.

The large-$N_c$ constraint yields,

$$\langle x^{n-1}\rangle_{(\Delta u-\Delta d)N\Delta} = \sqrt{2}\langle x^{n-1}\rangle_{(\Delta u-\Delta d)N}\left(1+\mathcal{O}(1/N_c^2)\right) , \tag{21}$$

where $\sqrt{2}$ is a ratio of Clebsch-Gordon coefficients. This result can be compared with the quark model one in Ref. [12].

In Ref. [7], we have calculated the leading-chiral logarithms in the moments of the quark helicity distributions of the nucleon:

$$\langle x^{n-1}\rangle_{(\Delta u-\Delta d)N} = \tilde{C}_n\left(1-\frac{2g_A^2+1}{(4\pi f_\pi)^2}m_\pi^2\log\left(\frac{m_\pi}{\mu^2}\right)\right) , \tag{22}$$

where $\tilde{C}_n = \langle x^{n-1}\rangle^0_{(\Delta u-\Delta d)N}$. The delta contributions can be calculated in the same way as shown in Ref. [8]. [An excellent introduction to the heavy delta formalism can be found in Ref. [13].] Here the contributions come in two ways: First, there is the delta-nucleon transition contribution from Fig. 1:

$$-\langle x^{n-1}\rangle^0_{(\Delta u-\Delta d)N\Delta}\frac{8g_A g_{\pi N\Delta}}{9(4\pi f_\pi)^2}J_2(\Delta, m_\pi) , \tag{23}$$

where

$$\begin{aligned} J_2(\Delta, m_\pi) = \quad & (3m_\pi^2-2\Delta^2)\log\left(\frac{m_\pi^2}{\mu^2}\right)+\frac{2\pi m_\pi^3}{\Delta} \\ & +2\frac{(\Delta^2-m_\pi^2)^{3/2}}{\Delta}\log\left(\frac{\Delta-\sqrt{\Delta^2-m_\pi^2+i\epsilon}}{\Delta+\sqrt{\Delta^2-m_\pi^2+i\epsilon}}\right) . \end{aligned} \tag{24}$$

Then there is the contribution from the quark-helicity distributions in the delta:

$$\langle x^{n-1}\rangle_{(\Delta u-\Delta d)\Delta^+}\frac{g_{\pi N\Delta}^2}{(4\pi f_\pi)^2}\frac{100}{9}J_1(\Delta, m_\pi) - \langle x^{n-1}\rangle_{(\Delta u-\Delta d)N}\frac{4g_{\pi N\Delta}^2}{(4\pi f_\pi)^2}J_1(\Delta, m_\pi) . \tag{25}$$

The above results are consistent with the one-loop chiral corrections to the axial vector coupling constant $g_A$ [14]. Assuming the large-$N_c$ relations,

$$\langle x^{n-1}\rangle_{(\Delta u-\Delta d)N\Delta} = \sqrt{2}\tilde{C}_n ,$$

we find

$$
\begin{aligned}
\langle x^{n-1}\rangle_{(\Delta u-\Delta d)N} \;=\; & \tilde{C}_n\left(1-\frac{2g_A^2+1}{(4\pi f_\pi)^2}m_\pi^2\log\left(\frac{m_\pi^2}{\mu^2}\right)\right. \\
& \left.-\frac{g_A^2}{(4\pi f_\pi)^2}\left[-\frac{4}{3}J_2(\Delta,m_\pi)+2J_1(\Delta,m_\pi)\right]\right)\ . \qquad (27)
\end{aligned}
$$

Using the physical values of $\Delta$ and $m_\pi$, we find that the delta contribution cancels about 60% of the nucleon contribution. A similar result applies for the transversity moments:

$$
\begin{aligned}
\langle x^{n-1}\rangle_{(\delta u-\delta d)N} = \; & \overline{C}_n\left(1-\frac{2g_A^2+1/2}{(4\pi f_\pi)^2}m_\pi^2\log\left(\frac{m_\pi^2}{\mu^2}\right)\right. \\
& \left.-\frac{g_A^2}{(4\pi f_\pi)^2}\left[-\frac{4}{3}J_2(\Delta,m_\pi)+2J_1(\Delta,m_\pi)\right]\right)\ . \qquad (28)
\end{aligned}
$$

where $\overline{C}_n=\langle x^{n-1}\rangle^0_{(\delta u-\delta d)N}$ is the moment in the chiral limit.

4. **Vector-isoscalar channel**:

Finally, we consider the isoscalar $\Delta u(x)+\Delta d(x)$ distribution. The twist-two operators $\mathcal{O}^{(n)i}_{\Delta u+\Delta d}$ are proportional to the angular momentum operator $J^i$. Due to the cancellation of the different spin orientations, their matrix elements in the nucleon and delta states are of order $N_c^{1-n}$ in $N_c$ counting. We can make the following expansion of the operators,

$$
\mathcal{O}^{(n)i}_{\Delta u+\Delta d}/N_c^{1-n}=a_0^{(n)}J^i+a_1^{(n)}\frac{G^{ij}T^j}{N_c}+a_2^{(n)}\frac{J^2J^i}{N_c^2}+\cdots\ . \qquad (29)
$$

Therefore, to order $1/N_c^2$, the distributions in the nucleon and $\delta$ are the same,

$$
\Delta u_N(x)+\Delta d_N(x)=(\Delta u_\Delta(x)+\Delta d_\Delta(x))\left(1+\mathcal{O}(1/N_c^2)\right)\ . \qquad (30)
$$

We have calculated the delta contribution to the chiral logarithms in the moments of the isoscalar quark helicity distribution,

$$
\delta\langle x^{n-1}_{(\Delta u+\Delta d)N}\rangle_{\text{from }\Delta}=-\frac{4g^2_{\pi N\Delta}}{(4\pi f_\pi)^2}J_1(\Delta,m_\pi)\left(\langle x^{n-1}_{(\Delta u+\Delta d)N}\rangle^0-\frac{5}{3}\langle x^{n-1}_{(\Delta u+\Delta d)\Delta}\rangle^0\right)\ , \qquad (31)
$$

which is identical to the scalar-isovector case. Assuming the large-$N_c$ relation, we have the sum of the $\pi$-delta and $\pi$-nucleon loop contributions,

$$
\delta\langle x^{n-1}_{(\Delta u-\Delta d)N}\rangle=\langle x^{n-1}_{(\Delta u+\Delta d)N}\rangle^0\frac{1}{(4\pi f_\pi)^2}\left[3g_A^2J_1(\Delta,m_\pi)-3g_A^2m_\pi^2\log\left(\frac{m_\pi^2}{\mu^2}\right)\right]\ , \qquad (32)
$$

which is subleading in $N_c$ counting.

Combining the relation in Eq. (30) with that from Eq. (18), we find

$$
\Delta u_\Delta(x)\;=\;\left[\frac{5+2T_z}{10}\Delta u_N+\frac{5-2T_z}{10}\Delta d_N\right]\left(1+\mathcal{O}(1/N_c^2)\right)\ ,
$$

In particular, for $\Delta^+$, we have $\Delta u_\Delta = (3\Delta u_N + 2\Delta d_N)/5$ and $\Delta d_\Delta = (2\Delta u_N + 3\Delta d_N)/5$. The same relation exits between the transversity distributions in the nucleon and delta.

One final comment: Since the chiral correction to the quark distributions in the nucleon is at relative order $1/N_c$ and since the relationships between the distributions in the delta and the nucleon are accurate up to relative order $1/N_c^2$, the chiral logarithms in the delta are connected to those in the nucleon by the same relations above.

To summarize, we have found large-$N_c$ relations between the quark distributions in the nucleon and delta, accurate to relative order $1/N_c^2$. The result can be used to make estimates of the delta contributions to the chiral logarithms in the quark distributions in the nucleon. Other uses of the quark distributions in the delta are also discussed briefly.

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